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П50

DETERMINATION OF SPRING ELEMENTS CHARACTERISTICS USING SHAPE MEMORY EFFECT DURING THERMOMECHANICAL IMPACT

ОПРЕДЕЛЕНИЕ ПАРАМЕТРОВ ПРУЖИННЫХ ЭЛЕМЕНТОВ С ЭФФЕКТОМ ПАМЯТИ ФОРМЫ В ПРОЦЕССЕ ТЕРМОМЕХАНИЧЕСКИХ ВОЗДЕЙСТВИЙ

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Abstract. Influence of the heat and mechanical treatment on the reversible change of shape on the cylindric compression springs with the shape memory effect under the cyclic change of temperatures during the intervals of martensite transformation is investigated. To obtain the optimal functional characteristics of the spring strength elements preheating conditions and the following heat and force cycling conditions were established. Using established relationships gives the possibility to estimate the effect of heat treatment in a new way and confirm the assumption that obtained experimental results are determined by the methods of research since the parameters single change characterizing effects of memory are thermomechanical training cycle. The obtained dependences define rational guidance of strain values and the required number of thermal cycles, providing stabilized characteristics of spring thermosensitive elements and the optimized parameters formation for memory effects data for thermosensitive elements geometric characteristics, and allow us to calculate and design thermal drive for technological systems.

Keywords: shape memory effect; shape memory alloy; thermosensitive element; actuating mechanism.

Аннотация. Исследовано влияние термической и термомеханической обработки на обратимое формоизменение при теплосменах цилиндрических пружин сжатия с эффектом памяти формы в интервале температур мартенситного превращения. Определены зависимости и установлены режимы предварительной термообработки и последующего термосилового циклирования для получения оптимизированных функциональных характеристик пружинных силовых элементов.

Ключевые слова: эффект памяти формы (ЭПФ); сплав с эффектом памяти формы (СПФ); термочувствительный элемент (ТЧЭ); термосиловой привод (ТСП).

Анотація. Досліджено вплив термічної й термомеханічної обробки на оборотне формовідновлення при теплозмінах циліндричних пружин стискання з ефектом пам'яті форми в інтервалі температур мартенситного перетворення. Визначено залежності та встановлено режими попередньої термообробки та подальшого термосилового циклування для отримання оптимальних функціональних характеристик пружинних силових елементів.

Ключові слова: ефект пам'яті форми; сплав з ефектом пам'яті форми; термочутливий елемент; термосиловий привід.

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PROBLEM STATEMENT

Schemes of the thermal power drivers (TPD) with thermally sensitive elements (TSE) in the form of coiled springs with shape memory effect (SME) are among the most promising, but insufficiently studied for implementation of the reciprocating motion of the deformation power elements and drivers of the cyclic operation technological systems. Thermally sensitive elements provide the best combination of the displacement values, simplicity of the parameters adjustment, an interval temperature response, high cyclic stability and simplicity of design and node layout [4, 5].

LATEST RESEARCH AND PUBLICATIONS ANALYSIS

There is not enough research involving the use of thermal power drivers based on alloys with shape memory effect. They are devoted to the study of influence of geometric parameters and rate recovery for characteristics of thermal power elements. The influence of thermal and thermomechanical treatment of alloys with shape memory effect hasn't been well studied. There is lack of information about spring thermal power elements.

The research aim is to study the influence of thermomechanical processing SME elements and the development of calculating methodology for thermally sensitive elements with shape memory to determine their geometric and deformation parameters as well as the development of modes of their thermomechanical processing.

BASIC MATERIAL

A number of scientific experiments based on application of spring samples made from NiTi alloys of ВСП-1 and TH-1K were carried out [1, 2, 3]. Based on theoretical investigations (the theory of large coiled spring displacements, the calculating methods of spring hardening) it has been possible to develop calculating methodology for TSE with SME in the form of cylindrical compressed springs with circular cross-section coils allowing to explain the geometrical parameters and compression charts. It's necessary for creation and development of corrective actuators based on TPD in engineering practice.

The obtained calculating methods allow us to determine geometrical and deformative- force parameters of TSE in the form of tension and compression springs which are used immediately after the final thermal-treatment in single acting mechanisms of the technological systems.

Subsequent TSE thermal cycling over the range of the phase transformation is accompanied by the gradual deformation accumulation in the direction of the applied voltage at the initial stage (because of nonclosuring thermomechanical hysteresis). It can be explained by the fact that other channels of deformation are simultaneously initiated with the conversion of the material ductility when the voltage is higher than yield of strength of the phase. These deformation channels are determined by the development of accommodative shifts, isothermal creep and dislocation plasticity.

Besides, it's possible to observe that a phase and material strain hardening increase yield strength dislocation and the degree of deformation reversibility. Isothermal creep rate decreases and stabilizes. Texturing martensite occurs. It means emergence and growth of the crystallographic options that provide the greatest TSE shape transformation in the direction of the applied load.

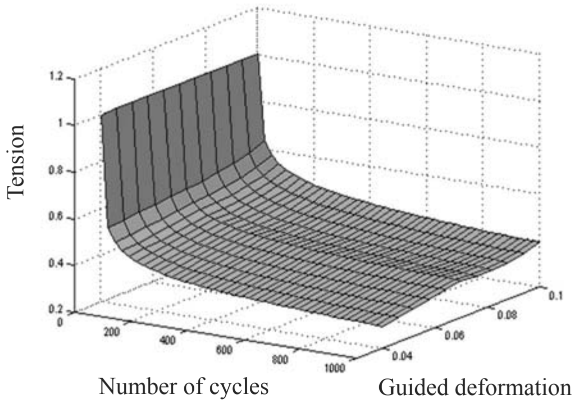
Forming of the naturally inherited defect structures (such as dislocation) leads to the specific transformation of metal lattice when the direct and inverse transformation are implemented according to the «forward-backward» principle.

As a rule, defect structure arising due to thermopower cycling is sharply anisotropic and fields of microstressing, locally oriented in space, are formed and their effect on the martensitic transformation is similar to the external load. As a result, thermally sensitive elements get the ability to accumulate deformation intensively at the half-cycle cooling period even in the absence of external load.

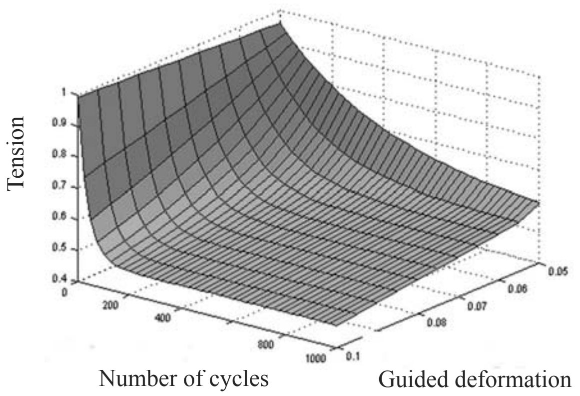
In the case of application of thermally sensitive elements in the thermopower drives schemes of cyclic and nonstop motion the final thermomechanical treatment in the form of stabilizing thermo-cycling should be implemented. On the basis of experimental data approximating dependences allowing us to estimate the changes in the deformation force characteristics of spring thermally sensitive elements made from TiNi were obtained in the process of thermo-cycling dependence on the number of cycles and deformation guidance.

Table 1. Material parameters of the spring TSE (ВСП-1 alloy)

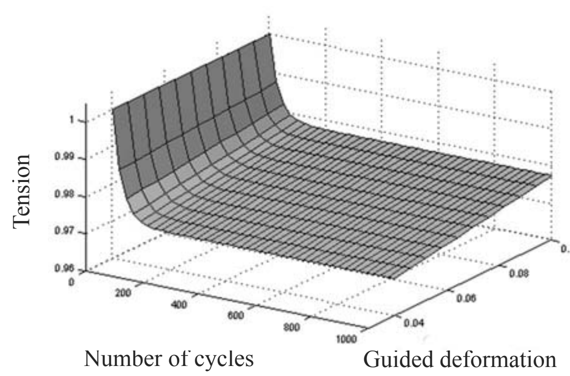
$u_i(\gamma_н)$	$\overline{\tau_н}$				$\overline{\tau'_н}$		$\overline{\tau_р}$		$\gamma_{ос}$		$\gamma_{об}$	
	A_i	B_i	C_i	D_i	A_i	B_i	A_i	B_i	A_i	B_i	A_i	B_i
u_0	3,404	$2{,}336\cdot10^{-4}$	–5,003	0,586	–1,859	0,659	0,124	0,965	0,226	$5{,}466\cdot10^{-3}$	0,43	$-2{,}188\cdot10^{-3}$
u_1	–3,404	1,003	5,084	0,411	2,794	0,255	–0,128	0,036	–0,226	$-5{,}314\cdot10^{-3}$	–0,446	$2{,}588\cdot10^{-3}$
u_2	–0,649	–0,222	3,524	–0,512	–0,481	0,021	–0,031	–0,028	0,049	–0,035	–0,302	–0,016



a)



b)



c)

Fig. 1. Changing the maximum stress and strain guidance reactive stresses in the TSC temperature sensing elements:

a — guidance deformation in the martensitic state; *b* — strain guidance in the implementation of the ETP; *c* — reactive voltage

Changing the maximum voltage guidance during deformation in martensitic state is described by the dependence of the following form:

$$\overline{\tau_н} = u_0(\gamma_н) + u_1(\gamma_н) N^{u_2(\gamma_н)}, \tag{1}$$

where $\overline{\tau_н} = \tau_N / \tau_{N=0}$; τ_N and $\tau_{N=0}$ are maximum voltage guided accordingly after N cycles and without TSC; $u_0(\gamma_н)$, $u_1(\gamma_н)$, $u_2(\gamma_н)$ are linear functions of the deformation guidance $\gamma_н$,

$$u_i(\gamma_н) = \begin{cases} A_i\gamma_н + B_i & \text{when } \gamma_н \le \gamma_{пр}; \\ C_i\gamma_н + D_i & \text{when } \gamma_н \ge \gamma_{пр}; \end{cases}$$

A_i, B_i, C_i, D_i are constants characterizing the cyclic properties of the alloy which are determined from the experimental data (the values of the constants A_i, B_i, C_i, D_i for spring TSE alloy WSP-1 are listed in Table 1); N is the number of thermal-cycles (see Fig. 1, *a*).

Standard deviation of the experimental data from calculated data, defined by the equation (1), does not exceed 2,4%.

Changing the maximum voltage guidance during the deformation in the range of martensitic transformation (in the implementation effect of the transformation plasticity (ETP)) is approximated by an exponential dependence of the form:

$$\overline{\tau'_н} = u_0(\gamma_н) + u_1(\gamma_н)\exp\left[u_2(\gamma_н)N\right], \tag{2}$$

where $\overline{\tau'_н} = \tau_N / \tau_{N=0}$; $u_i(\gamma_н) = A_i\gamma_н + B_i$.

Standard deviation of the experimental data from calculated data, defined by the equation (2), does not exceed 2,5% (see Fig. 1, *b*).

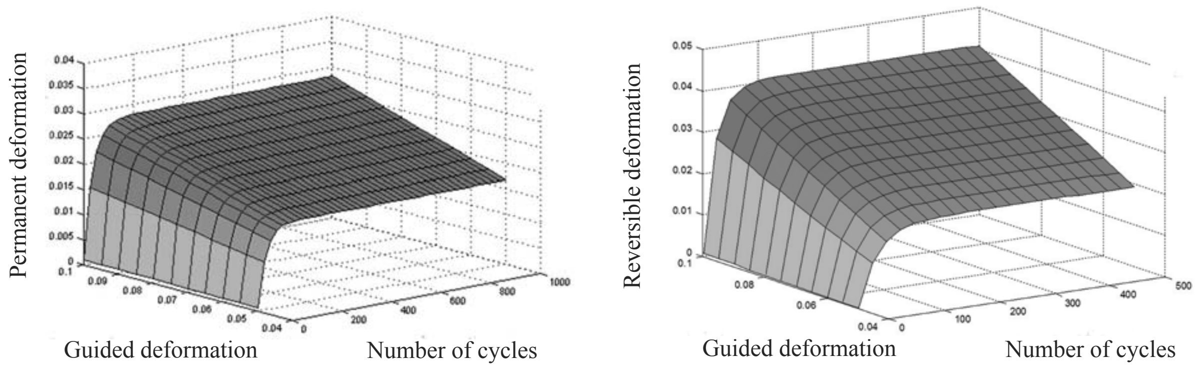
Changing the maximum reactive voltage (implementation of SME) also occurs on an exponential function (see Fig. 1, *c*):

$$\overline{\tau_р} = u_0(\gamma_н) + u_1(\gamma_н)\exp\left[u_2(\gamma_н)N\right],$$

where $\overline{\tau_р} = \tau_р / \tau_{рN=0}$; $\tau_р$ and $\tau_{рN=0}$ are maximum reactive stresses, respectively, after N cycles and without TSC; $u_i(\gamma_н) = A_i\gamma_н + B_i$.

Standard deviation of the experimental data from calculated data, determined by the equation $\overline{\tau_р} = \varphi(N, \gamma_н)$, is less than 1,5%.

Effect of TSC and the strain prompting on total residual strain $\gamma_{ос}$ and reversible deformation $\gamma_{об}$ (accumulates in the implementation of reversible SME) can be described by the same exponential dependences.



a) *b)*

Fig. 2. Changing total deformations TSE during TSC:
a — the residual strain; *b* — reversible deformation

Surfaces $\gamma_{\text{ос}} = \varphi(N, \gamma_{\text{н}})$ and $\gamma_{\text{об}} = \varphi'(N, \gamma_{\text{н}})$ are presented in Fig. 2, *a*, *b* and have standard deviation from the experimental data which is less than 2%.

CONCLUSIONS. Using of established relationships gives the possibility to estimate the effect of heat treatment in a new way and confirm the assumption that obtained experimental results are determined by the methods of research since the parameters single change, characterizing effects of memory, is thermomechanical training cycle.

The obtained dependences define rational guidance of strain values and the required number of thermal cycles N, providing stabilized characteristics of spring TSE and the formation of optimized parameters of memory effects for the given TSE geometric characteristics, and allow us to calculate and design thermal drives for technological systems.

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